Reexamination of reaction rates for a key stellar reaction of ^{14}O(α,p)^{17}F

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The reaction rates of the key stellar reaction of ^{14}O(α,p)^{17}F have been reexamined. The previous conclusion, the 6.15-MeV state (J^π=1$^-$) dominating this reaction rate, has been overthrown by a careful reanalysis of the previous experimental data [J. Gómez del Campo *et al.*, Phys. Rev. Lett. **86**, 43 (2001)]. According to the present R-matrix analysis, the previous 1$^-$ assignment for the 6.15-MeV state is definitely wrong. Most probably, the 6.286-MeV state is the 1$^-$ state and the 6.15-MeV state is a 3$^-$ one, and hence the resonance at E_x=6.286 MeV (J^π=1$^-$) dominates the reaction rates in the temperature region of astrophysical interests. The newly calculated reaction rates for the ^{14}O(α,p)^{17}F reaction are quite different from the previous ones, for instance, it's only about 1/6 of the previous value around 0.4 GK, while it's about 2.4 times larger than the previous value around 2 GK. The astrophysical implications have been discussed based on the present conclusions.

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Explosive hydrogen and helium burning are thought to be the main source of energy generation and a source for the nucleosynthesis of heavier elements in cataclysmic binary systems, for example, x-ray bursters, *etc.* [1–3]. During an x-ray burst (a high temperature and high density astrophysical site), Hydrogen and Helium rich material from a companion star form an accretion disk around the surface of a neutron star where the H and He transferred from the disk begin to pile up. The αp chain is initiated through the reaction sequence ^{14}O(α,p)^{17}F(p,γ)^{18}Ne(α,p)^{21}Na [4], and increase the rate of energy generation by 2 orders of magnitude [3]. In x-ray burster scenarios, the nucleus ^{14}O($t_{1/2}$=71 s) forms an important waiting point, and the ignition of the ^{14}O(α,p)^{17}F reaction at temperatures ∼0.4 GK produces a rapid increase in power and can lead to breakout from the hot CNO cycles into the rp-process with the production of medium mass proton-rich nuclei [5–7]. Excepting the ^{15}O(α,γ)^{19}Ne reaction, this reaction is arguably the most important reaction to be determined for x-ray burster scenarios.

Wiescher *et al.* [8] calculated the reaction rates of the ^{14}O(α,p)^{17}F reaction, and shown that the resonant reaction rates dominated the total rates above temperature 0.4 GK. However, Funck *et al.* [9, 10] found that direct-reaction contributions to the ℓ=1 partial wave are comparable to or even greater than the resonant contributions at certain temperatures. Because the resonant reaction rates of ^{14}O(α,p)^{17}F depend sensitively on the excitation energies, spins, partial and total widths of the relevant resonances in ^{18}Ne, Hahn *et al.* [11] extensively studied the levels in the compound system ^{18}Ne [11] by several reactions, such as, ^{16}O(^{3}He,n)^{18}Ne,^{12}C(^{12}C,^{6}He)^{18}Ne as well as ^{20}Ne(p,t)^{18}Ne reactions. Based on the firmer experimental results, they concluded that this reaction rate, in the important temperature regime ∼0.5-1 GK, was dominated by reactions on a single 1$^-$ resonance at an excitation energy of 6.150 MeV lying 1.036 MeV above the ^{14}O+α threshold energy of 5.114 MeV. Harss *et al.* [12] studied the time reverse reaction ^{17}F(p,α)^{14}O in inverse kinematics with ^{17}F beam at Argonne, and identified three levels at 7.16, 7.37, 7.60 MeV and determined their resonance strengths as well. Later, Gómez del Campo *et al.* [13] used the p(^{17}F,p) resonant elastic scattering on a thick CH$_2$ target to look for resonances of astrophysical interest in ^{18}Ne at ORNL. In the region investigated, they located four resonances at excitation energies of 4.52, 5.10, 6.15, and 6.35 MeV in ^{18}Ne, and J$^\pi$=1$^-$, 2$^-$ were respectively assigned to the last two states based on their R-matrix analysis. Subsequently, Harss *et al.* [14] extracted the resonance strength and the width Γ_α for the 6.15-MeV state based on this 1$^-$ assignment together with the excitation function obtained from their previous work [12]. Recently, the inelastic component of this key 1$^-$ resonance in the ^{14}O(α,p)^{17}F reaction has been studied by a new highly sensitive technique at ISOLDE/CERN [15], and found that this inelastic component will enhance the reaction rate, contributing approximating equally to the ground-state component of the reaction rate, however not to the relative degree suggested in Ref. [16].

As a summary, all the previous discussions and calculations [11, 14–16] related to the reaction rates of ^{14}O(α,p)^{17}F are based on the 1$^-$ assignment for the 6.15-MeV state. In this Letter, we completely overthrown this assignment by a carefully reanalyzing the experimental data measured at ORNL [13], and the astrophysical consequences have been discussed based on the present new assignments.

In the present analysis, the multichannel R-matrix calculations [17–19](see example [20]) that include the energies, widths, spins, angular momenta, and interference

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sign for each candidate resonance have been performed with a channel radius of r_0=1.25 fm (R=r_0×(1+17$^{1/3}$)), appropriate for the ^{17}F+p system. The difference between the code we used and the `MULTI` code [21] utilized in the previous work [13] is negligibly small, which ensures the correctness of the present R-matrix analysis. The ground state spin-parity configurations of ^{17}F and the proton are $5/2^+$ and $1/2^+$, respectively, and therefore the channel spin in the elastic channel can have two values s=2, 3.

The fitting curve shown in the upper panel of Fig. 2 in [13] has been exactly reproduced by utilizing their resonant parameters, *i.e.*, E_{cm}=0.6 MeV, 3^+, Γ=18 keV; E_{cm}=1.18 MeV, 2^+, Γ=45 keV (1.18 MeV was mistyped by 1.118 MeV in [13]); and the last 'dip' structure can be reproduced by the following parameters: E_{cm}=1.53 MeV, 2^-, Γ=5 keV, which is consistent with the results of Ref. [11] (Γ≤20 keV). However, according to our R-matrix analysis, 1^- assignment for the 6.15-MeV state is absolutely impossible (see fitting curves labeled by 'fit1' and 'fit2' in FIG. 1(a)), the shape of the 1^- resonance (ℓ=1) is of a 'dip' structure instead of a 'bump' one. In addition, all possible combinations of different spin-parity assignments for these two states have been attempted and the most probable fitting curves are shown

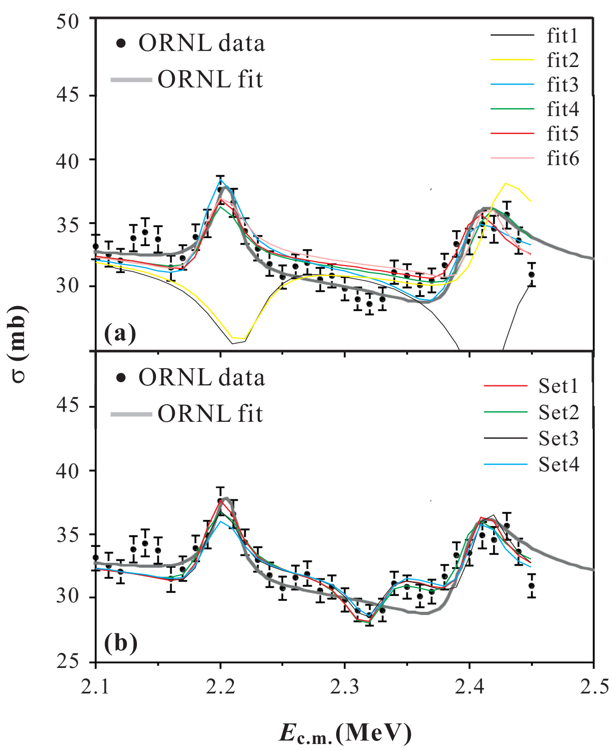

FIG. 1: R-matrix fits for the experimental data measured at ORNL [13]. The vertical scale corresponds to the angle integrated cross sections in the range $\theta_{\rm CM}$=162°∼178°. (a) fitting for two resonances, (b) fitting for three resonances. All curves are convoluted by an assumed 10-keV energy resolution except those two labeled by 'fit1' and 'fit2'. For comparison, the ORNL fit is shown as well. See text for details.

TABLE I: Resonant parameters used in FIG.1. Here resonance energies (E_r) are in units of MeV, and proton partial widths (Γ_p) in keV. The parameters in 'fit1' and 'fit2' were used in the previous work [13]. See text for details.

Sets	Resonance 1			Resonance 2			Resonance 3		
	E_{r1}	$J^\pi[\ell,s]$	Γ_p	E_{r2}	$J^\pi[\ell,s]$	Γ_p	E_{r3}	$J^\pi[\ell,s]$	Γ_p
fit1[a]	2.22	1^-[1, 2]	50	2.42	2^-[1, 3]	50			
fit2[a]	2.22	1^-[1, 2]	50	2.42	2^-[1, 2]	50			
fit3[b]	2.20	3^-[1, 3]	15	2.39	3^-[1, 2]	30			
fit4[b]	2.20	2^-[1, 2]	15	2.41	2^-[1, 2]	30			
fit5[b]	2.20	3^-[1, 3]	10	2.40	2^-[1, 2]	20			
fit6[b]	2.20	2^-[1, 2]	20	2.41	3^-[1, 3]	10			
Set1[b]	2.20	3^-[1, 3]	12	2.40	2^-[1, 2]	20	2.32	1^-[1, 2]	15
Set2[b]	2.20	2^-[1, 2]	20	2.40	2^-[1, 2]	20	2.32	1^-[1, 2]	15
Set3[b]	2.20	3^-[1, 3]	10	2.41	3^-[1, 3]	12	2.32	1^-[1, 2]	15
Set4[b]	2.20	2^-[1, 2]	15	2.41	3^-[1, 3]	10	2.33	1^-[1, 2]	12

[a] no energy-resolution convolution in the fits of FIG.1; [b] a 10-keV energy-resolution convolution in the fits of FIG.1.

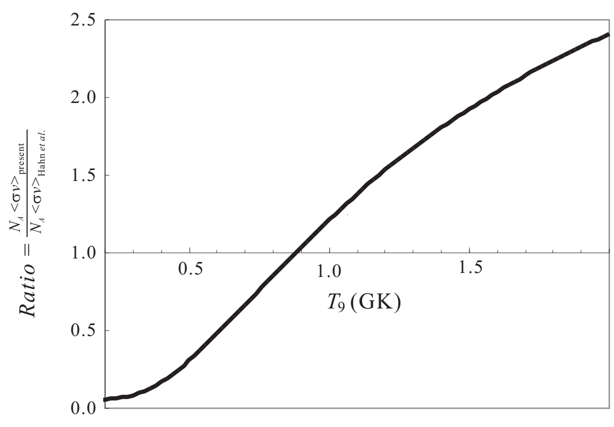

FIG. 2: The ratios between the present resonant reaction rates and those previous ones at certain temperature range. See text for details.

in FIG. 1(a) with parameters listed in Table 1. In order to achieve a better fit, all curves are convoluted by an assumed 10-keV energy resolution except those two labeled by 'fit1' and 'fit2', of course this will not affect the spin-parity assignments for the resonances. Furthermore, we have tried to fit the experimental data shown in the lower panel of Fig. 2 in [13] with three resonances, and the most probable fitting curves are shown in FIG. 1(b) with parameters listed in Table 1. It's very obvious this kind of three-resonance fits reproduce the experimental data better than those two-resonance ones, especially the 'dip' structure at E_{cm}=2.32 MeV can be fitted very well.

The present R-matrix analysis shows that two states at E_{cm}=2.20(E_x=6.12), 2.40(E_x=6.32) both possibly have J^π=2^- or 3^-, while the state at E_{cm}=2.32(E_x=6.24) most probably has J^π=1^-. These three states should correspond to the E_x=6.150, 6.345, and 6.286 MeV states observed before [11] within a ∼30 keV uncertainty. In order to constrain the spin-parity assignments for these

states, let's examine the well-known mirror nucleus ^{18}O, which has only three known levels J^{π}=1$^-$,(2$^-$), and 3$^-$ around this energy region [11]. The strong population of the 6.15-MeV state in the ^{16}O(^{3}He,n)^{18}Ne reaction [11] suggests it has natural parity, which eliminates the possibility of J^{π}=2$^-$. According to the above R-matrix analysis, it's absolutely not a 1$^-$ state, and therefore it should be a 3$^-$ state. The results from the ^{12}C(^{12}C,^{6}He)^{18}Ne and ^{20}Ne(p,t)^{18}Ne reactions suggest that 6.286-MeV state is of natural parity and 6.345-MeV state of unnatural parity. Therefore, we propose that these two states most probably have 1$^-$ and 2$^-$, respectively. Actually Funck *et al.* [9] predicted a 1$^-$ state at 6.294 MeV. The ORNL experimental data can be reproduced very well with these assignments (see fitting curve labeled by 'Set1' in FIG. 1(b)).

In the temperature region interesting for x-ray burster scenarios [11, 14, 15], only two natural-parity states, *i.e.*, E_x=6.150 (J^{π}=3$^-$, ℓ_{α}=3), 6.286 (J^{π}=1$^-$, ℓ_{α}=1), are needed to calculate the reaction rates of ^{14}O(α,p)^{17}F. Our new assignments for these two states are just contrary to the previous ones [11]. The previously calculated Γ_{α} partial widths are 2.2, 0.34 eV for the 6.150, 6.286 MeV states, respectively. According to the relationship of $\Gamma_{\alpha} \propto C^2 S_{\alpha} \times P_{\ell}(E_r)$ [22], the presently calculated Γ_{α} partial widths are 0.051, 13.4 eV for these two states, respectively. Accordingly, the calculated resonant strength $\omega\gamma_{(\alpha,p)}$ are 0.36, 40 eV, respectively, while they were 6.6, 2.4 eV in the previous work [11]. As a consequence, the roles of these two resonances in contributing the resonant reaction rate of ^{14}O(α,p)^{17}F are exchanged, and now the resonance at E_x=6.286 MeV (J^{π}=1$^-$,ℓ_{α}=1) dominates the total reaction rates within the temperature region of interests (0.4$\sim$3 GK). The resonant reaction-rate ratios between the present results and the previous ones [11] are plotted in Fig. 2, here only two resonances (E_x=6.150, 6.286 MeV) are included in the calculations. It can be seen that the present reaction rate is quite different from the previous one, for instance, it's only about 1/6 of the previous value around 0.4 GK but, about 2.4 times larger than the previous one around 2 GK. According to the present analysis, we think the 1$^-$ assignment for the 6.286-MeV state is quite reasonable, and hence the spin-parity assignments for the 6.150, 6.345 MeV states are rather unimportant in calculating the reaction rates (*i.e.*, whether they are J^{π}=2$^-$,3$^-$, or vice versa).

The present rates confirms that the ^{14}O(α,p)^{17}F reaction is rather unlikely to be dominant component in the hot CNO cycles in novae environments (instead ^{15}O(α,γ)^{19}Ne reaction is, see discussions in [11]). Due to the present rate enhancements above 0.9 GK, this reaction can, however, contribute strongly to the breakout from the hot CNO cycle under the more extreme conditions in x-ray bursters. The present conclusion could probably affect the onset temperature where the α-capture dominates β-decay and a breakout from the hot CNO cycle via ^{14}O(α,p)^{17}F reaction begins to take place [8]. In addition, the present conclusion shows that the previous inelastic-scattering contributions [15, 16] to the total reaction rates of ^{14}O(α,p)^{17}F could be neglected. The detailed reaction rate calculations for this key reaction and its astrophysical implications will be published later [23].

Acknowledgments

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